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EURADOS
European Radiation Dosimetry Group e.V.

Politecnico di Milano

9th EURADOS Winter School "Dosimetry for epidemiological cohorts"

Dosimetry for uranium miners

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11.02.2016

Dosimetry for uranium miners

Introduction

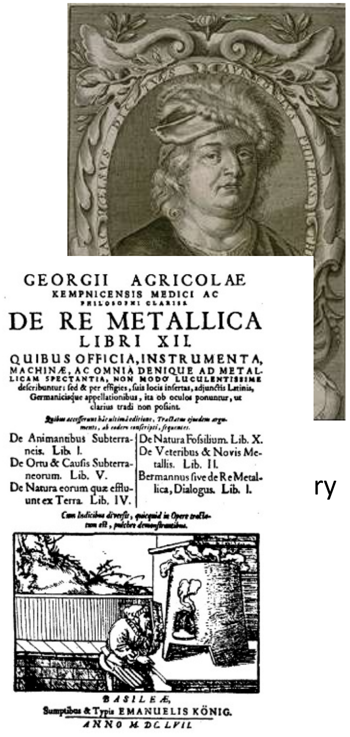
Methods

The WISMUT cohort

The EU Concerted action CURE

Interest for miners as an exposed population

- Paul Schneevogel (Paulus Niavis, ca.1460-1517) in his book **Iudicium Iovis: Das Gericht der Götter über den Bergbau** describes the lung diseases occurring in the silver mines of Saxony and Bohemia, implying that they are due to the "*dangerous air in the depth of the earth*".
- Paracelsus (Philippus Aureolus Theophrastus Bombastus von Hohenheim, 1493-1541) called "*mala metallorum*" the lung disease plaguing the miners of Schneeberg and Joachimsthal (today Jachimov, in the Czech Republic).
- Georg Agricola (ca. 1530- 1575), in his book **De re metallica**, recommends to ventilate the mines in order to avoid the "miners' sickness" («*Bergsucht*»).
- In 1879 Walther Hesse und Friedrich Hugo Härting published the study **Der Lungenkrebs, die Bergkrankheit in den Schneeberger Gruben** identifying lung cancer as the sickness of the miners in Schneeberg.



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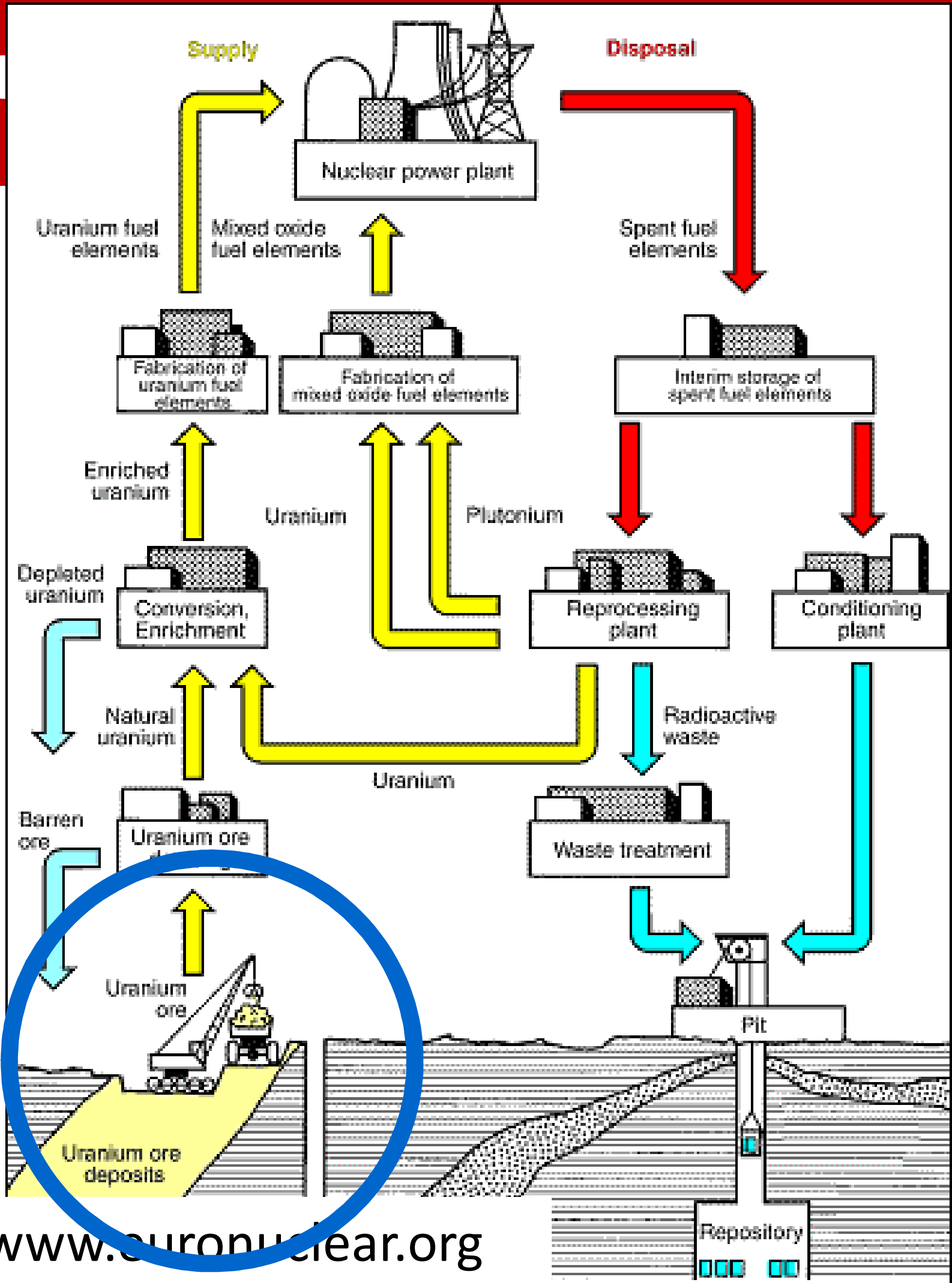
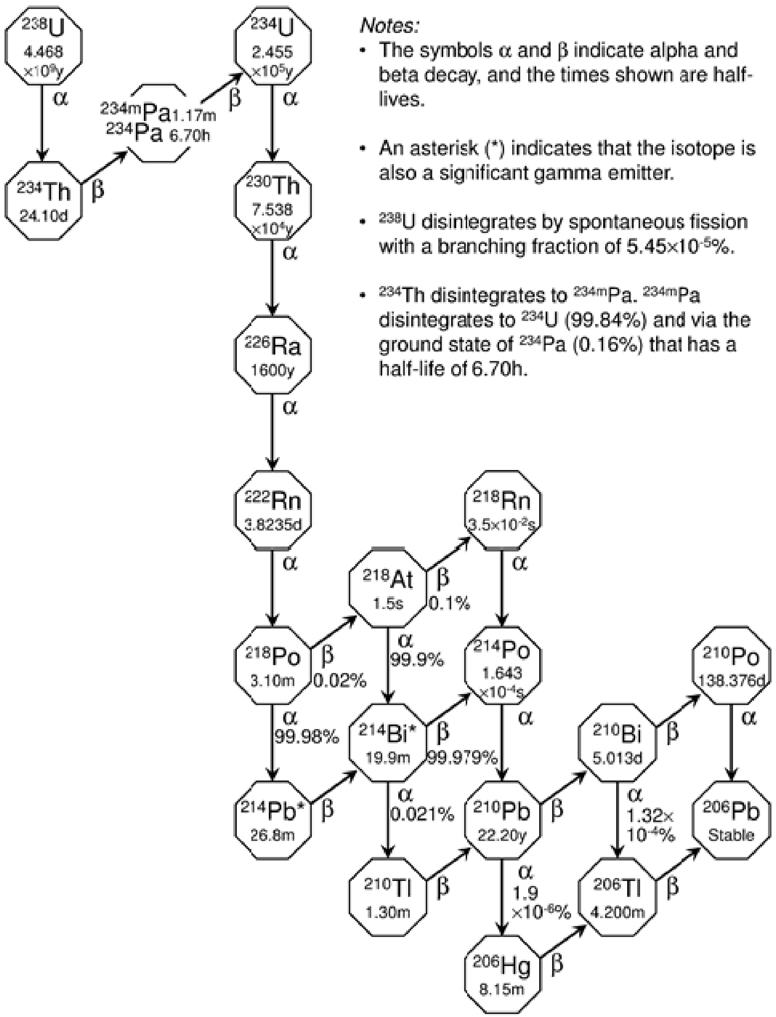
www.mineralogicalrecord.com

Interest for miner … on



Graphics from www.euronuclear.org

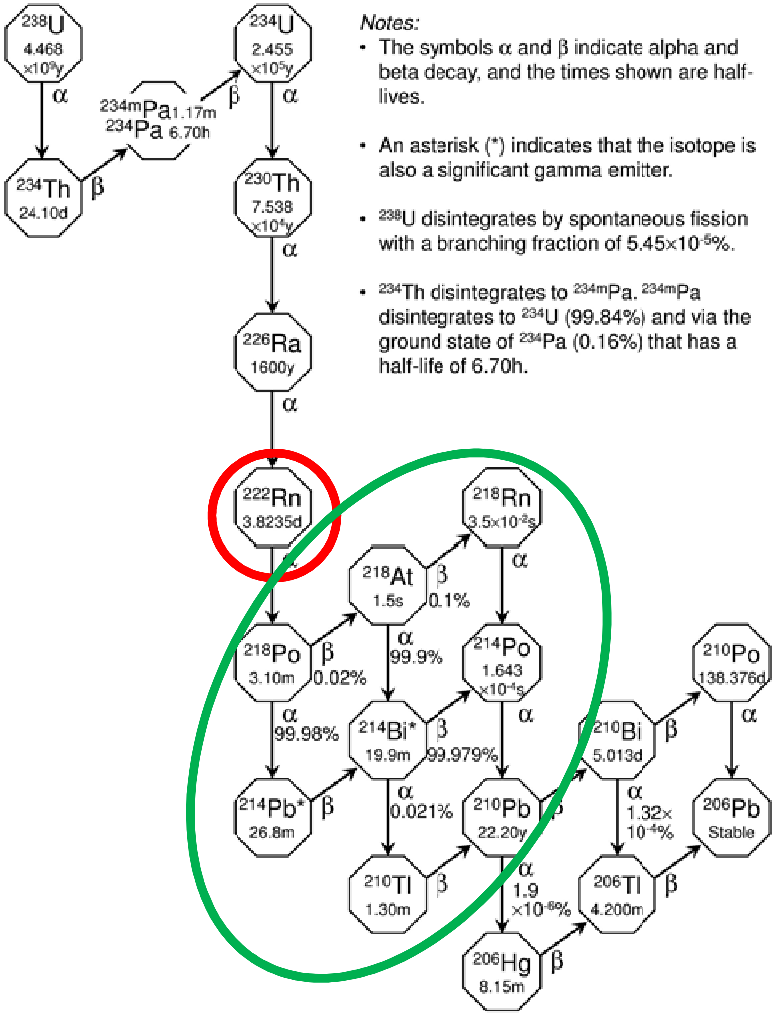
Uranium and other radionuclides in the rocks



Notes:

- The symbols α and β indicate alpha and beta decay, and the times shown are half-lives.
- An asterisk (*) indicates that the isotope is also a significant gamma emitter.
- ^{238}U disintegrates by spontaneous fission with a branching fraction of 5.45×10^{-5}%.
- ^{234}Th disintegrates to ^{234m}Pa. ^{234m}Pa disintegrates to ^{234}U (99.84%) and via the ground state of ^{234}Pa (0.16%) that has a half-life of 6.70h.

Among uranium progeny there is a gas!



Among uranium progeny there is a gas!

Radon gas (Bq·m^{-3})

Radon progeny

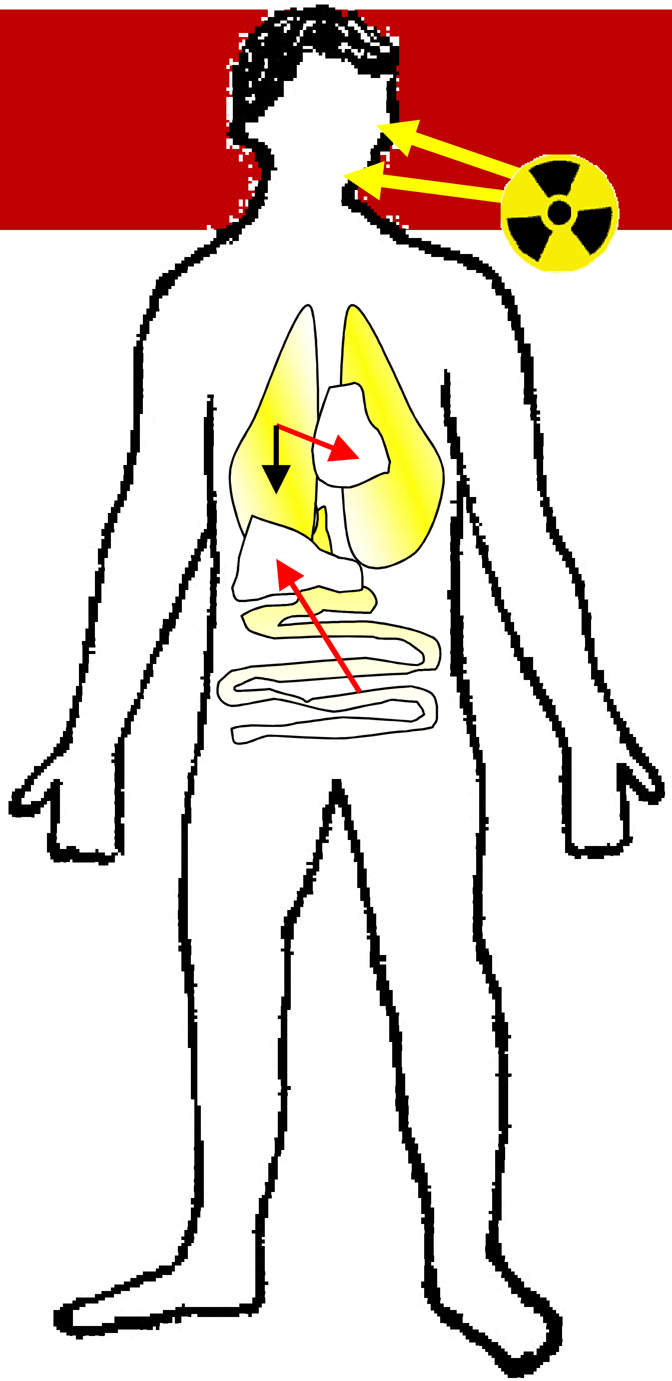
F = equilibrium factor (e.g., ventilation)

f_p = unattached fraction

Aerosol characteristics (e.g., use of diesel motors)

Uranium ore dust (Long lived radionuclides)

Radon gas and progeny and ore dusts are inhaled by the miners



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Bundesamt für Strahlenschutz

Sources of exposure for the miners

<u>Gamma (low LET):</u>

External (radionuclides in the ores)

~ homogeneous exposure of all organs

Internal (radon progeny, LLR in the ore dust)

<u>Alfa and beta (high/low LET):</u>

Internal (radon gas, radon progeny, LLR in the ore dust)

Very inhomogeneous, depending on the deposition pattern

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Uranium and other radionuclides in the rocks

D_T = Organ absorbed dose (Gy)

K_{air} = air-kerma, free in air (Gy)

D_{air} = dose to air, free in air (Gy)

$D_{T,air} = 1.1 \cdot D_{air} = 1.1 \cdot K_{air}$

$D_{T,air}$ = Tissue dose, free in air (Gy)

$D_T = F_b \cdot D_{T,air} = 1.1 \cdot F_b \cdot K_{air}$

Ambient dose equivalent H*(10)

Personal dose equivalent $H_p(10)$

Typical values:

F_b: ~ 0.65

D_T/H*(10) ~ 0.6

$D_T/H_p(10)$ ~ 0.9

Conversion coefficients (D_T/K_{air}) can be found in ICRP Publication 116 (Sv/Gy)

Internal dose due to inhalation

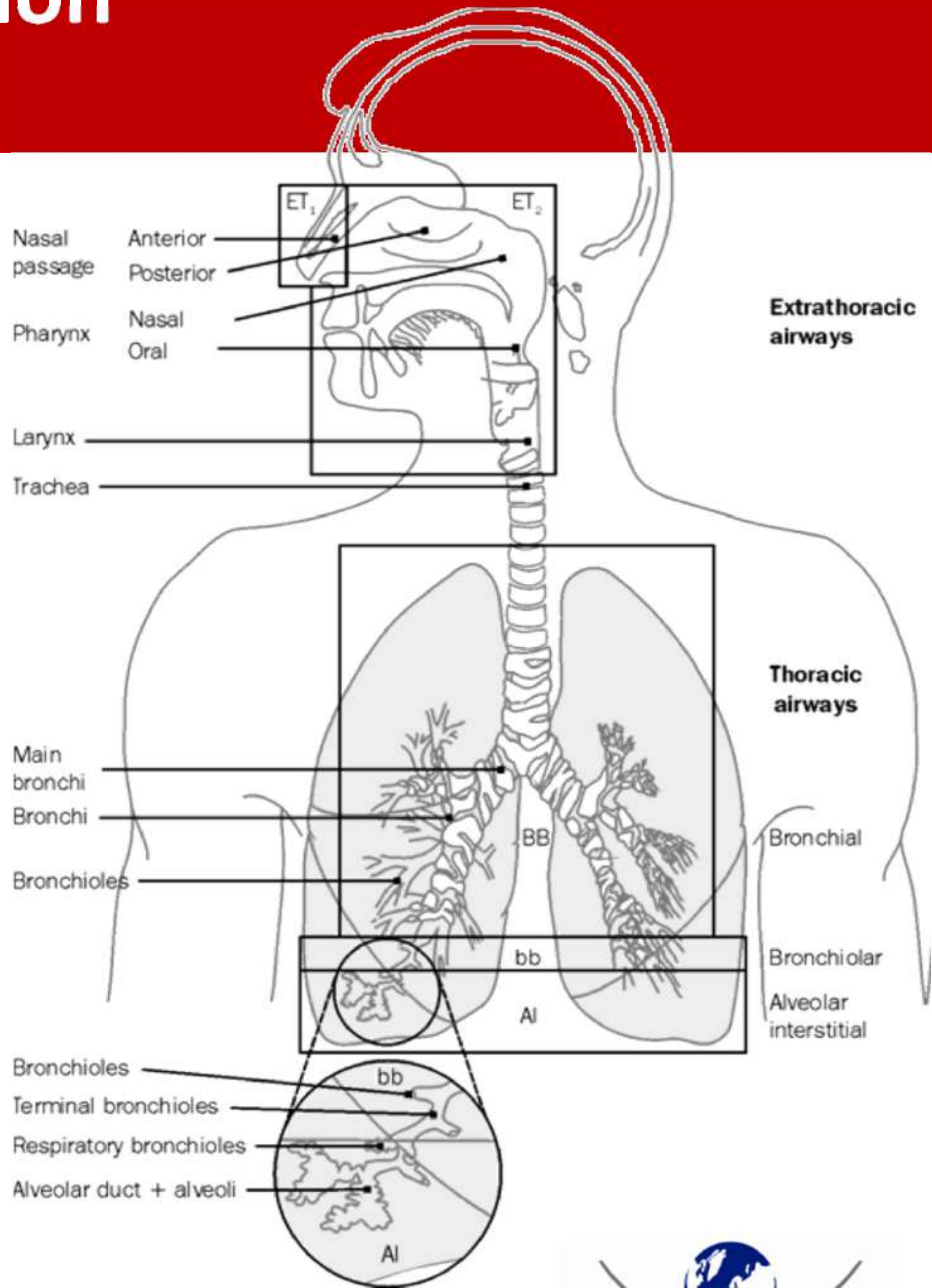
ICRP Publication 66 (1994)

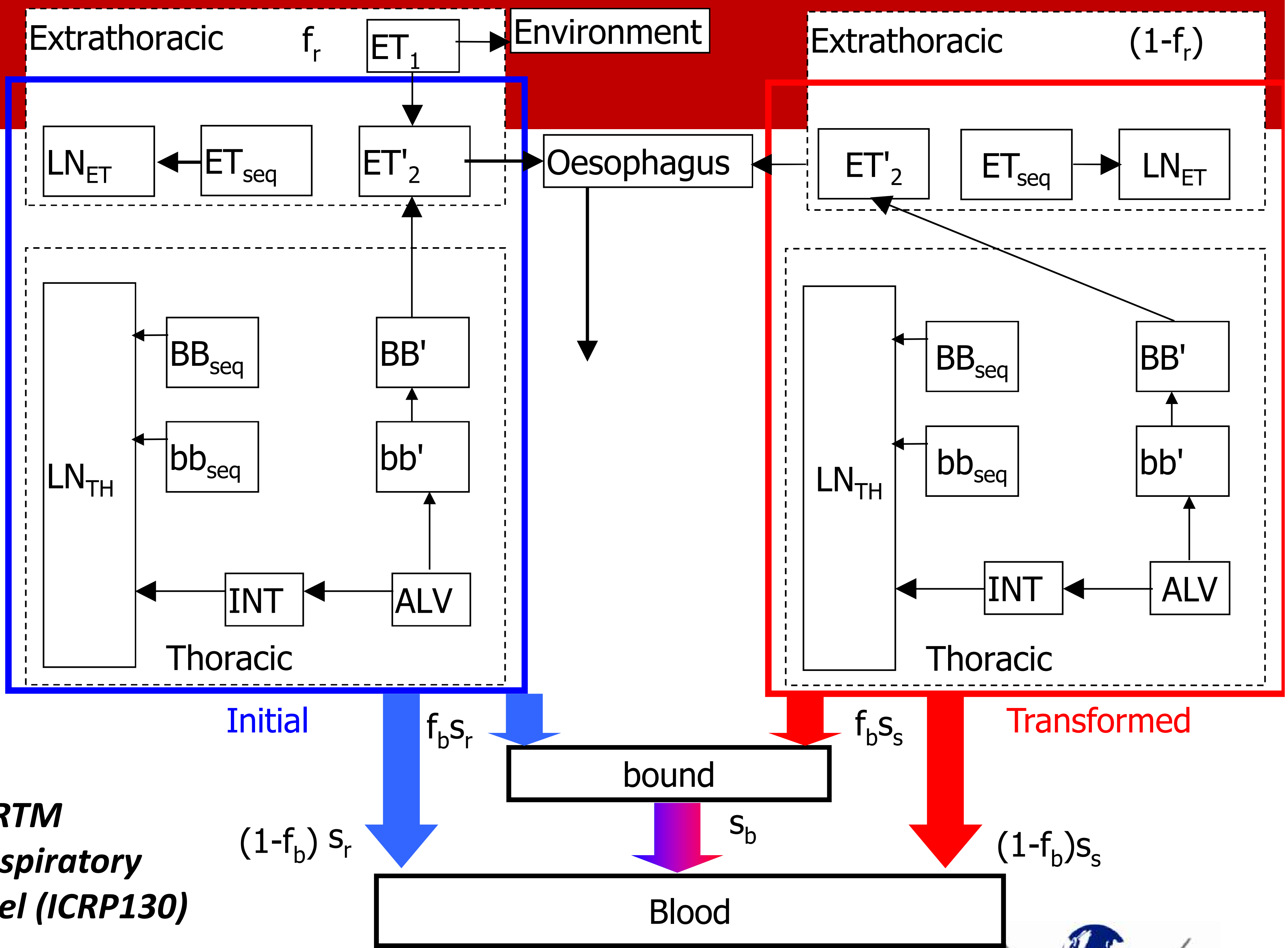
Human respiratory tract model

deposition, particle transport and absorption to blood after inhalation

ICRP reports on Occupational Intakes of Radionuclides (OIR)

- Revised HRTM (**ICRP Publication 130, 2015**)
- Systemic models





Revised HRTM
Human Respiratory
Tract Model (ICRP130)

Internal dose due to inhalation

- Environmental data
  - Radon progeny ($J \cdot m^{-3} \cdot h$ or WLM)
  - Radon gas ($Bq \cdot m^{-3} \cdot h$)
  - Long-lived radionuclides including uranium ($Bq \cdot m^{-3} \cdot h$)
- Parameters of exposure
  - Breathing rate ($m^3 \cdot h^{-1}$)
  - Radon progeny : equilibrium factor F, unattached fraction f_p
  - Long-lived radionuclides : isotopic composition
  - Particles sizes: median diameter AMTD/AMAD and standard deviation σ_g
  - Absorption in lung (f_r, s_r, s_s)
- Job types
  - Wet/dry drilling, ventilation, diesel, physical activity

Photo PC Guiollard

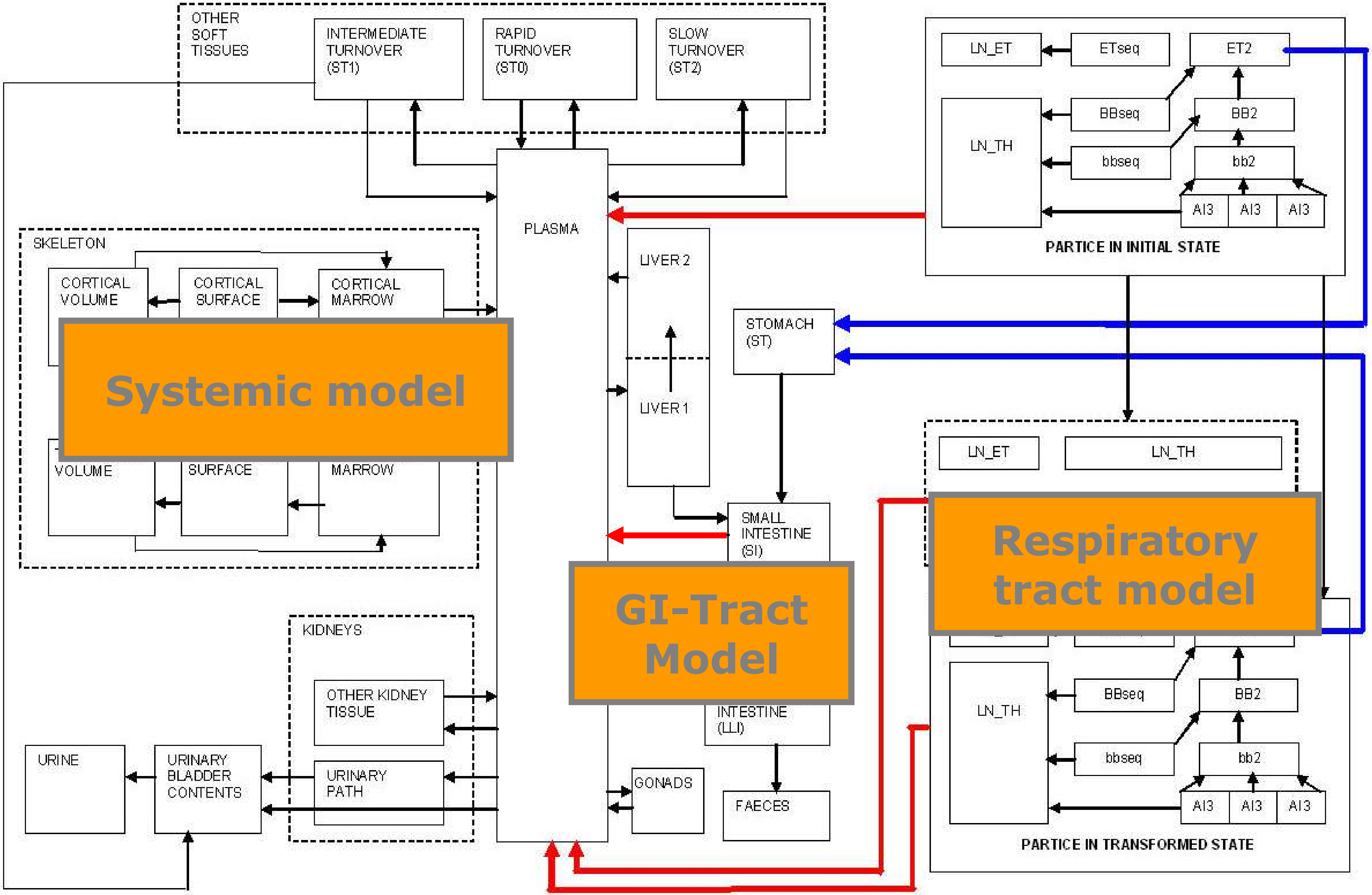
INTAKE

Internal dose due to inhalation - AlphaRisk

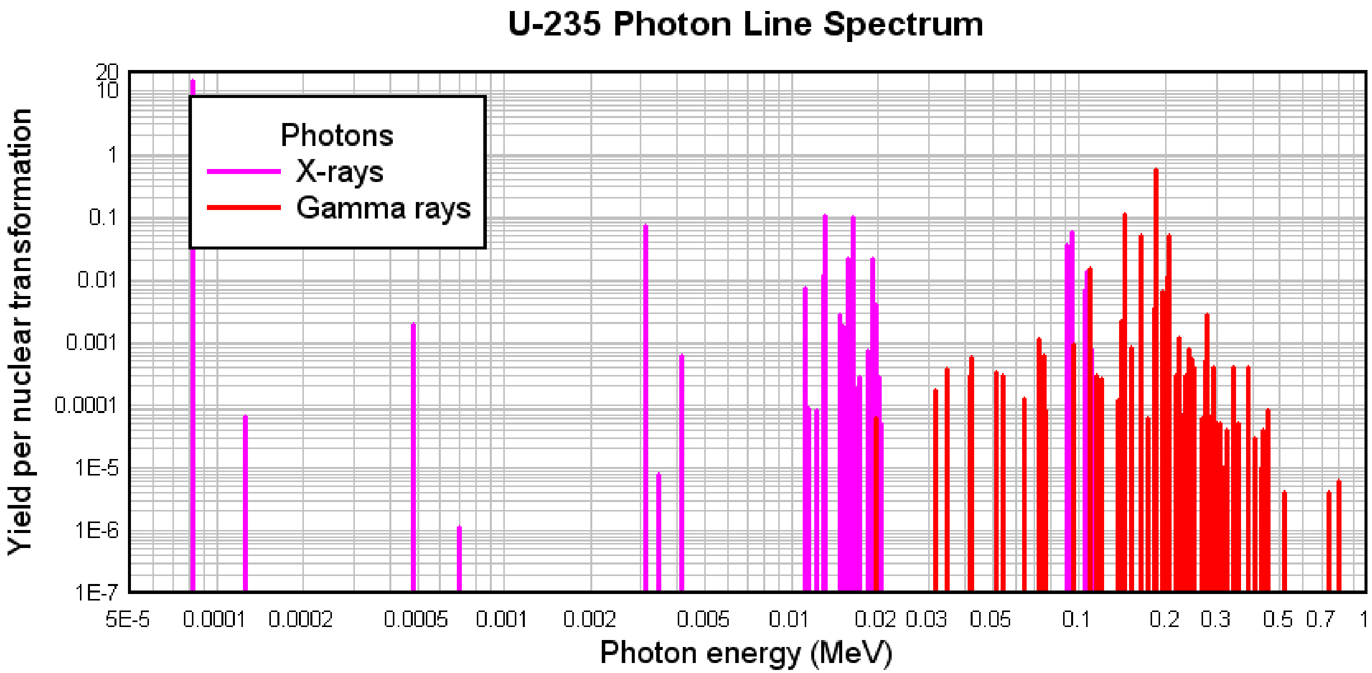
Exposure scenario	Job type	Mode[a]	Aerosol fraction of PAEC[b]	AMTD[c]/AMAD[d] (nm)	σ_g[e]	hgf[f]	F[g]
Wet drilling + good ventilation + diesel	0	u	0.006	0.8[c]	1.3	1	0.2
		a	0.994	200[d,h]	2.0	1	
Wet drilling + good ventilation	1	u	0.03	0.8[c]	1.3	1	0.25
		a	0.97	350[d]	2.2	1.5	
Wet drilling + med ventilation	2	u	0.01	0.8[c]	1.3	1	0.4
		a	0.99	250[d]	2.2	1.5	
Wet drilling + poor ventilation	3	u	0.01	0.8[c]	1.3	1	0.6
		a	0.97	250[d]	2.2	1.5	
Dry drilling with poor ventilation	4	u					0.6
		a					

HRTM absorption parameters	Unattached radon progeny[b]	Attached radon progeny[c]
Rapid dissolution fraction, f_r	1	0.06
Rapid dissolution rate, s_r (d^{-1})	1000	67
Slow dissolution rate, s_s (d^{-1})		1.4 (12 h half-time)
Bound fraction, f_b	0.8	
Uptake rate from bound state, s_b (d^{-1})	1.7 (10 h half-time)	

Marsh et al.,
Radiat. Prot. Dosim. 2012, **149**:371-83


OTHER SOFT TISSUES
INTERMEDIATE TURNOVER (ST1)
RAPID TURNOVER (ST0)
SLOW TURNOVER (ST2)
PLASMA
SKELETON
CORTICAL VOLUME
CORTICAL SURFACE
CORTICAL MARROW
VOLUME
SURFACE
MARROW
Systemic model
LIVER 2
LIVER 1
STOMACH (ST)
SMALL INTESTINE (SI)
GI-Tract Model
INTESTINE (LLI)
GONADS
FAECES
KIDNEYS
OTHER KIDNEY TISSUE
URINARY PATH
URINARY BLADDER CONTENTS
URINE
LN_ET
ETseq
ET2
LN_TH
BBseq
BB2
bbseq
bb2
AI3
AI3
AI3
PARTICE IN INITIAL STATE
LN_ET
LN_TH
Respiratory tract model
LN_TH
BBseq
BB2
bbseq
bb2
AI3
AI3
AI3
PARTICE IN TRANSFORMED STATE

Radiation transport calculations with anthropo-morphic phantoms and Monte Carlo techniques



Nuclear database and computational phantom (from **ICRP Publications 107 and 110**)

Dosimetry for uranium miners

German WISMUT cohort – Follow-up 1945-2008

Former employees of the WISMUT uranium mining company (1946-1989) in East Germany

Selection of 4,054 men who worked in a milling facility, but never underground or in open pit mining (to avoid high radon concentrations)

	Total cohort	Millers
#	58,982	4,054
Person-Years	2.2 Mio	158,383
Mean duration of follow-up (yrs)	37	39
Loss to Follow-Up	2,138 (3.6%)	79 (1.9%)
Deceased cohort members	25,438 (43.1%)	1,671 (41.2%)
Cause of death available	23,939 (94%)	1,587 (95%)

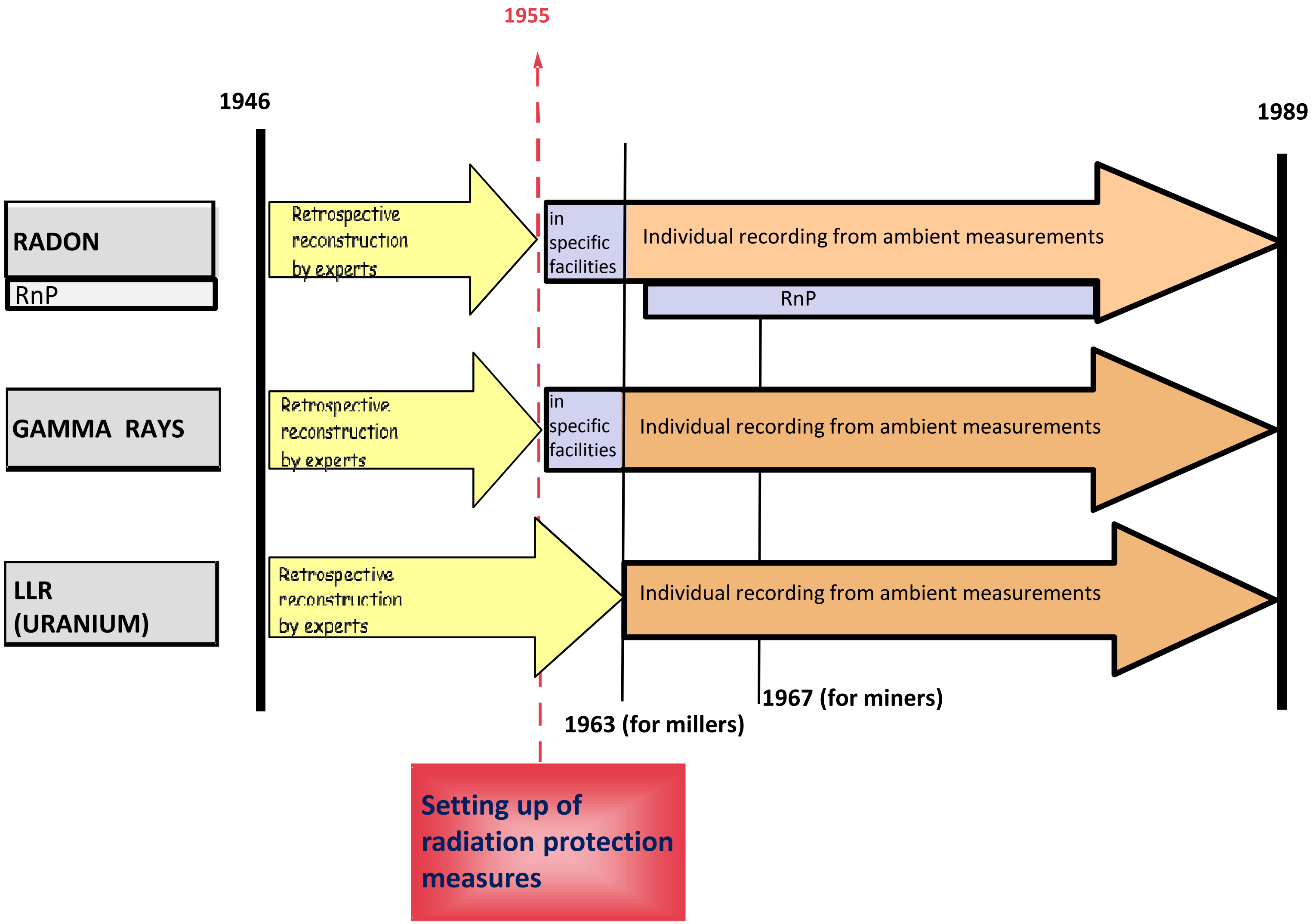
German WISMUT cohort – Job-Exposure Matrix

- Exposure to radon progeny, long-lived radionuclides from uranium ore dust and external gamma radiation were determined from a comprehensive job-exposure matrix (JEM) that assigns an exposure to each calendar year (1946 –1989), facility, work place (underground, milling, open pit mining, surface) and job activity (n = 900)
- These exposures were based on ambient measurements taken either after 1954 for radon progeny and long-lived radionuclides from uranium ore dust or after 1963 for gamma doses. Prior to these years, the relevant exposures were based on detailed expert rating.

Job-Exposure matrix - millers

- Definition of two reference facilities with measurements
- Measurements made for 28 different work process stages (e.g., belt transport, grinding/crushing, leaching/filtration, precipitation, concentrate drying, etc.)
- Retrospective assessment of exposure taking into account parameters related to uranium production, milling techniques,..
- For 141 job types, the average time spent in the work process stages as defined above was determined, and a time-weighted average exposure across the work process stages estimated

Exposure assessment in the WISMUT mines



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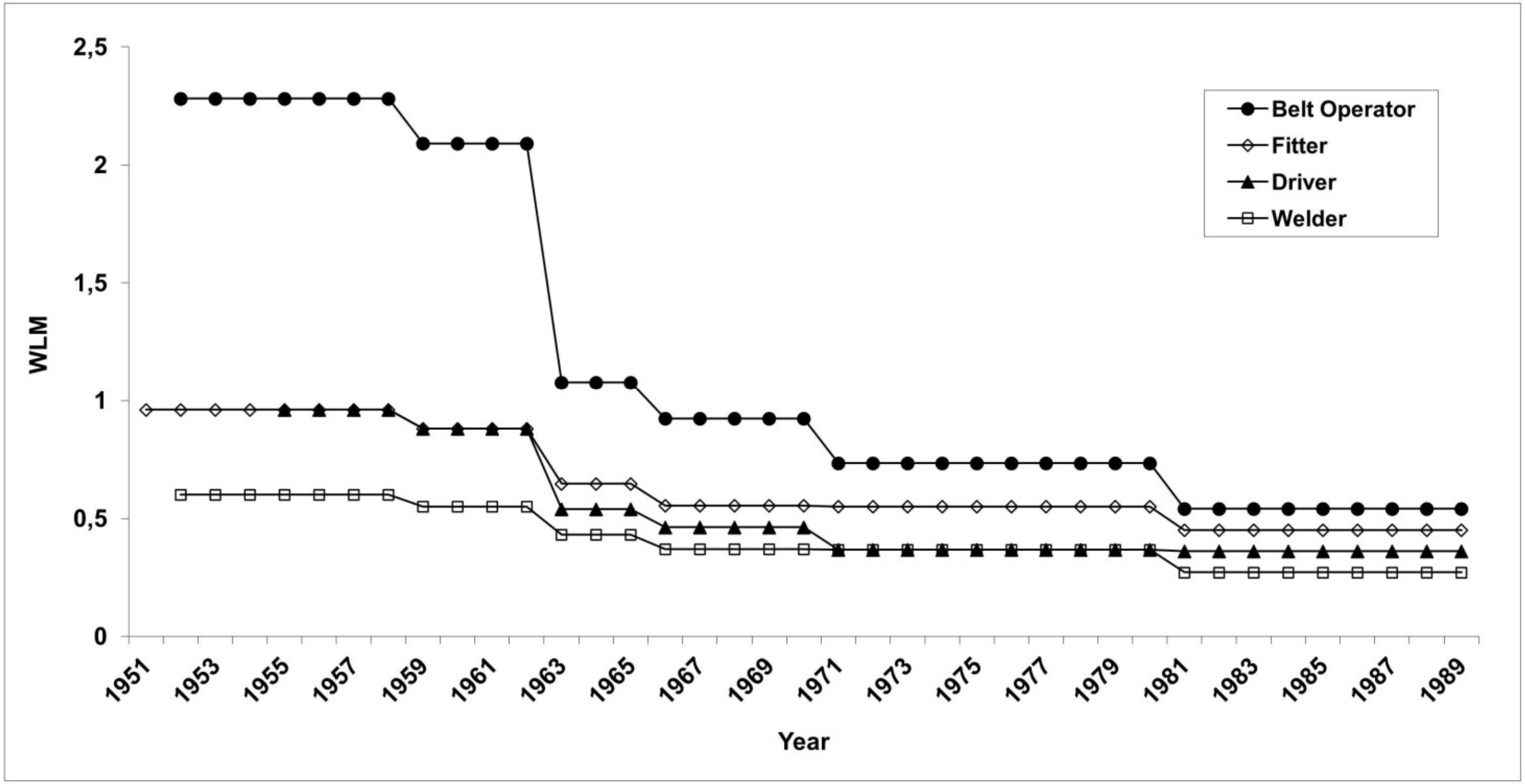
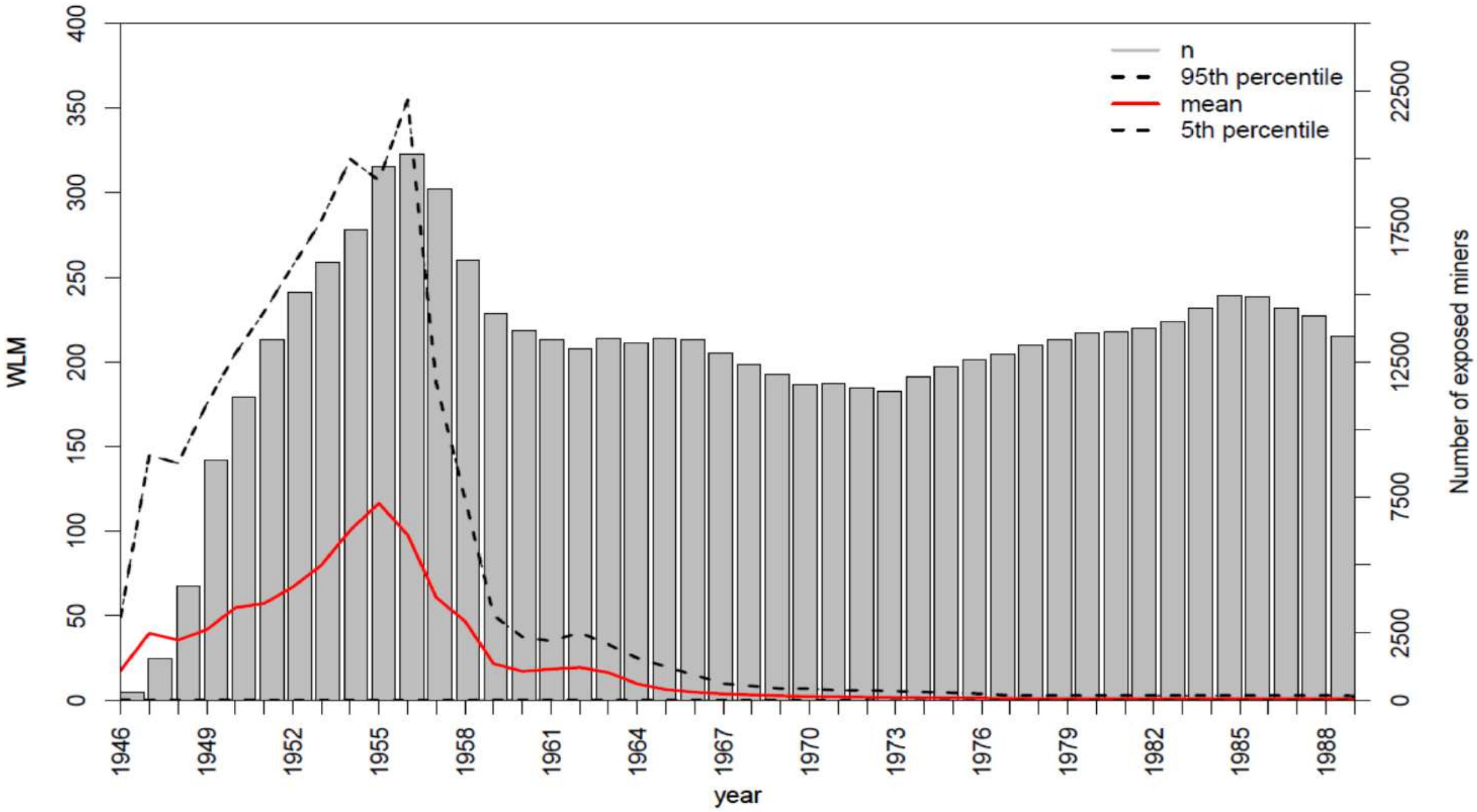
Example: Annual exposure to radon progeny for the four most frequent job types in the facility Crossen



Kreuzer et al., Int. Arch. Occup. Environ. Health 2015, **88**:431-41

Annual radon progeny exposure in the miners' cohort



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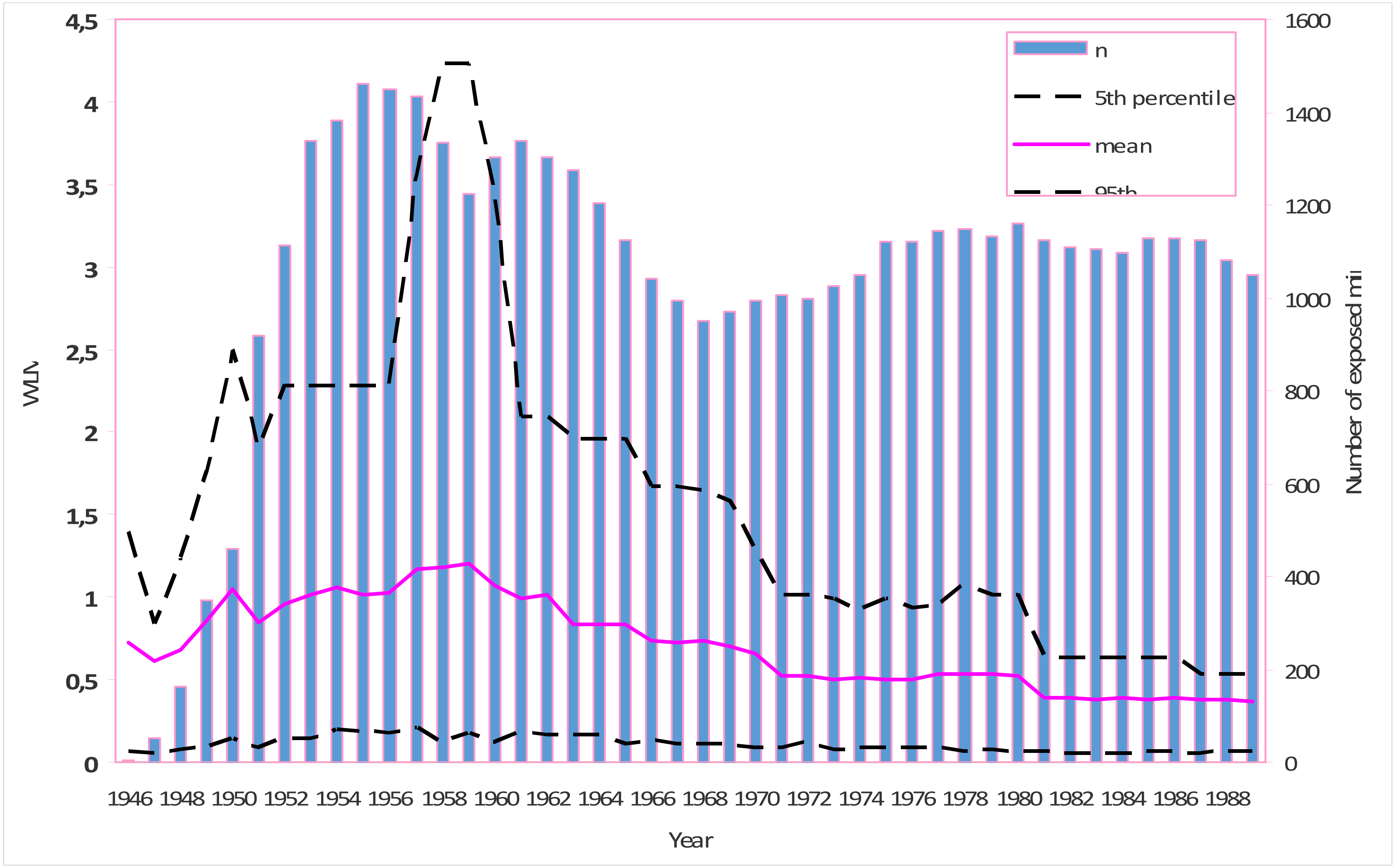
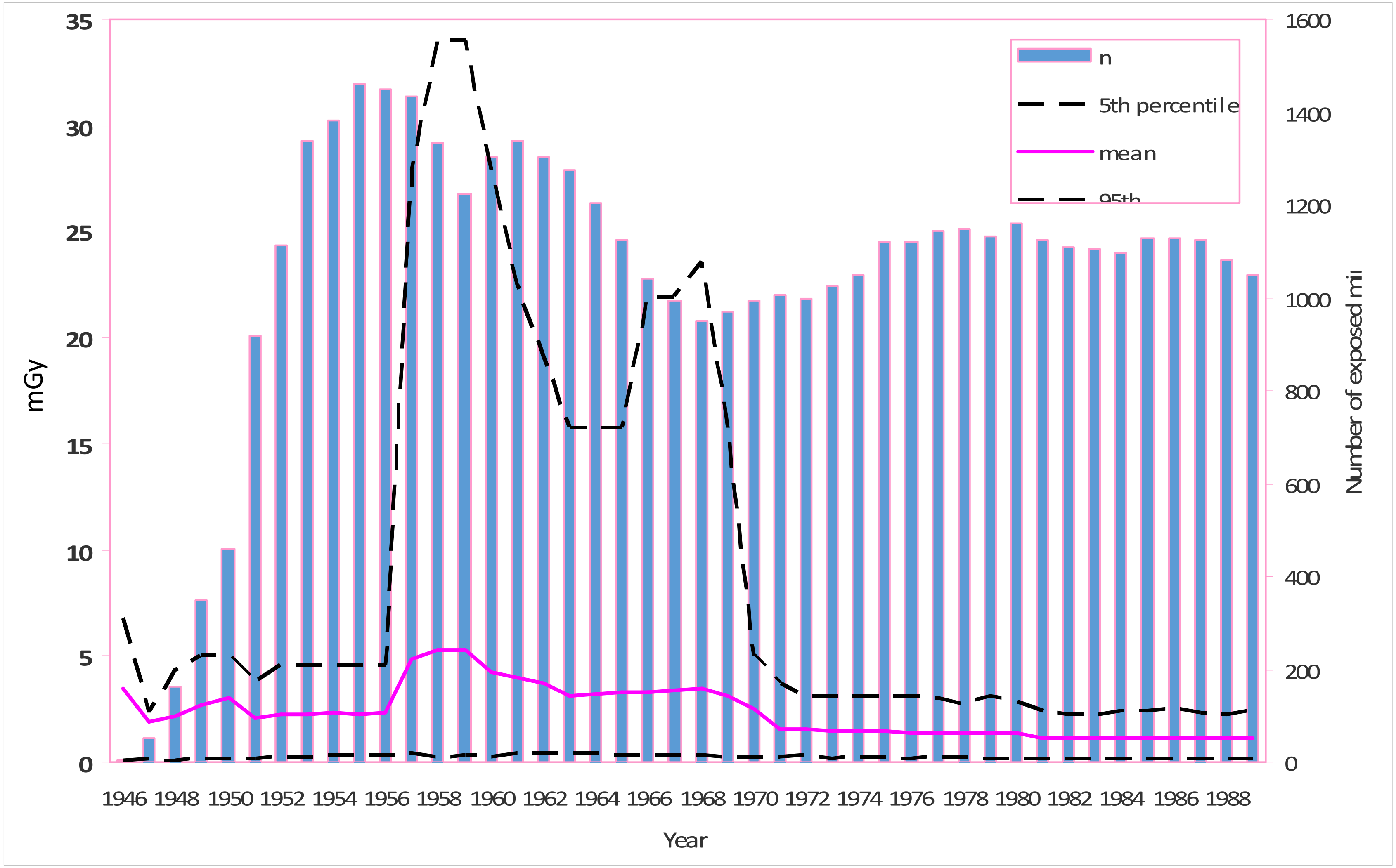
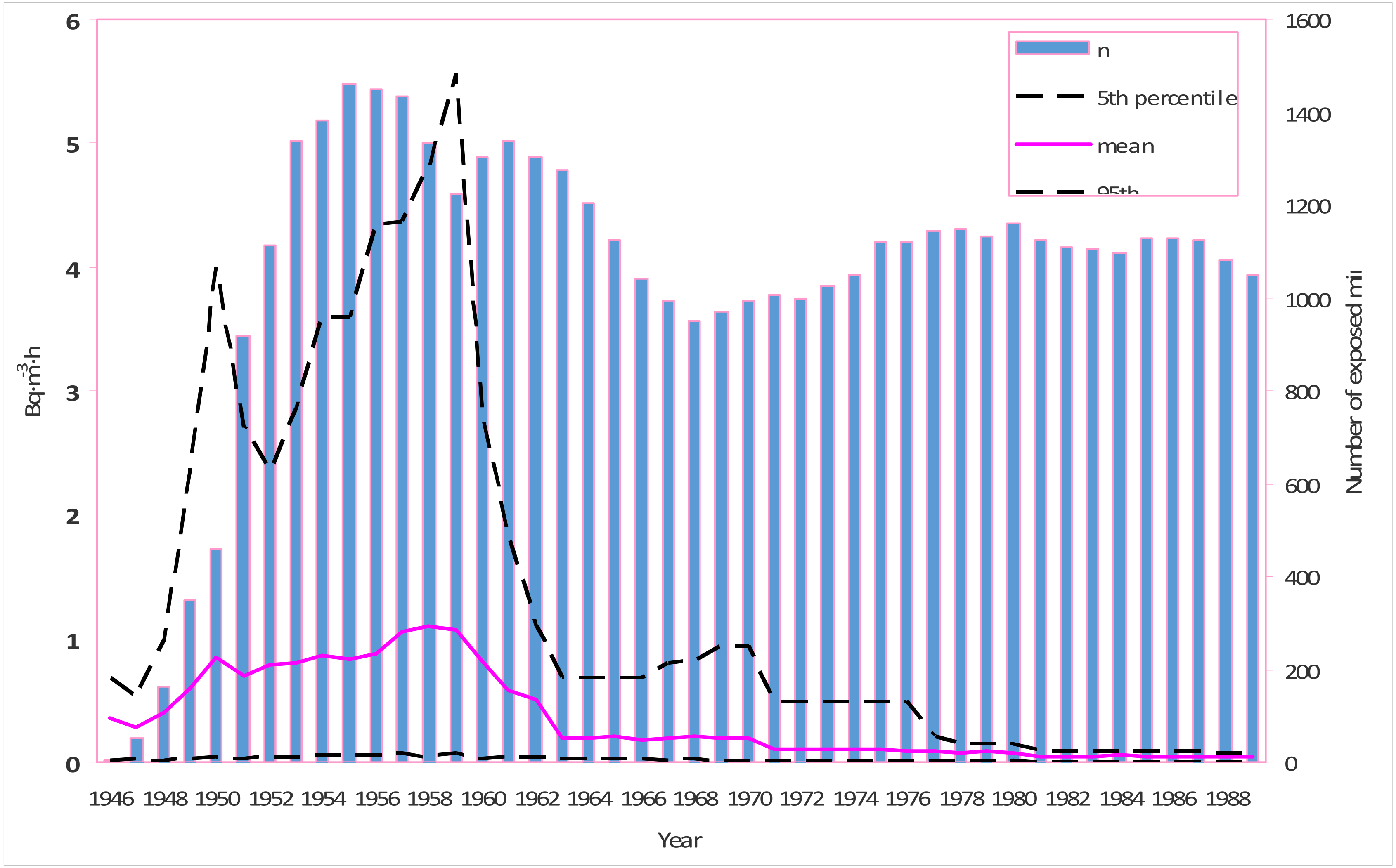
Annual radon progeny exposure in the millers' cohort



Annual gamma exposure in the millers' cohort



Annual LLR exposure in the millers' cohort



Cumulative exposure to radiation (mean values)

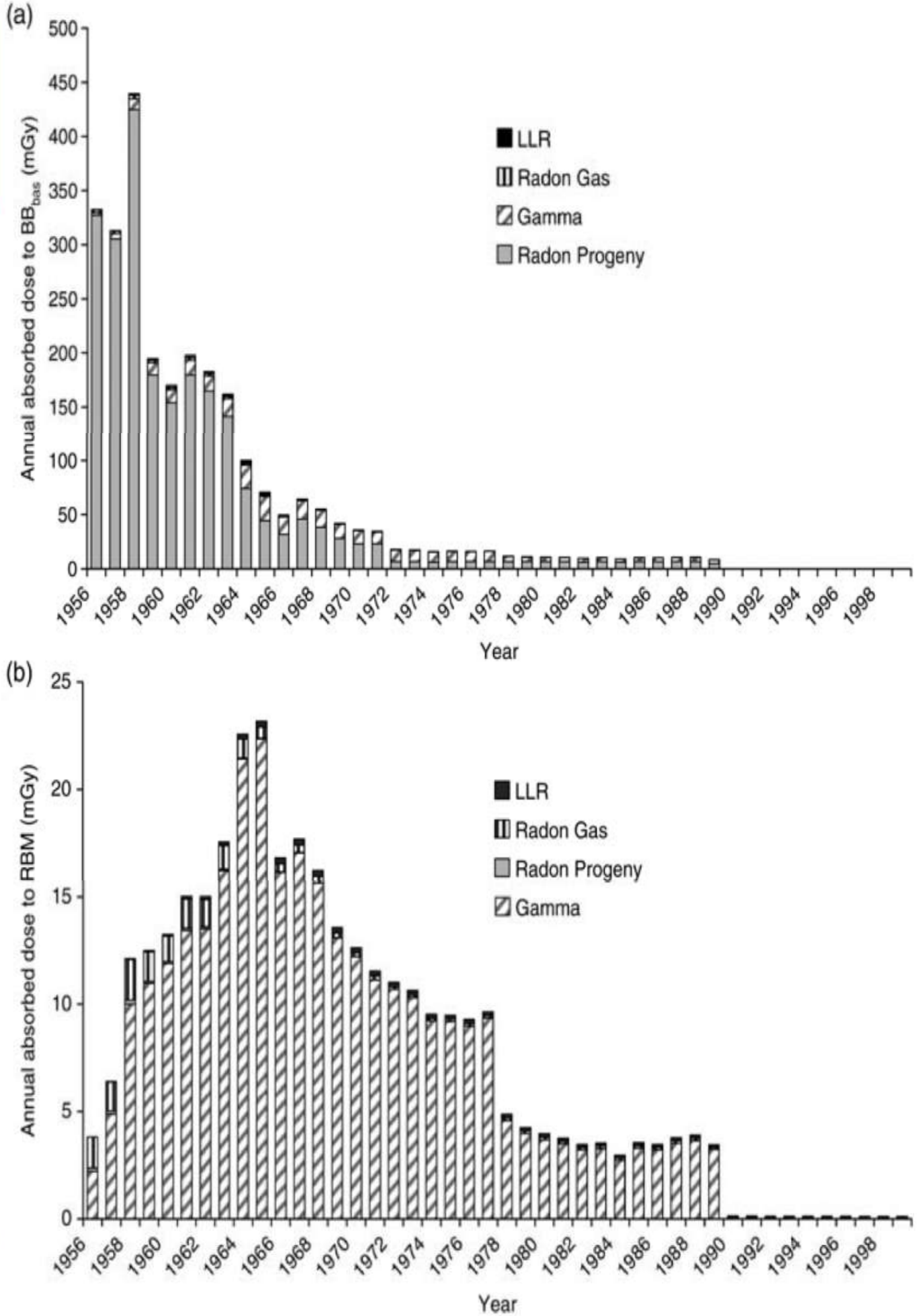
	Miners (underground)	Millers
Radon progeny [WLM]	326	8
External gamma radiation [mGy]	54	26
Long-lived radionuclides in uranium ore dust [$kBq \cdot h \cdot m^{-3}$]	4.1	3.9

WLM: Working Level Months

Kreuzer et al., Int. Arch. Occup. Environ. Health 2015, **88**:431-41

Individual dose calculation

Marsh et al.,
Radiat. Prot. Dosim. 2012,
149:371-83



Cumulative absorbed organ doses among exposed members of the Wismut cohort (n=50,770)

Organ	Mean (mGy)					Max (mGy)
	Rn progeny	Rn gas	LLR	Gamma	Total	Total
Lung	1,556	13.6	3.2	47	1,620	24,089
Kidney	9	0.5	0.4	47	58	1,005
RBM	1	7.6	0.9	47	57	941
Liver	1	1.0	0.8	47	50	989
Stomach	11	0.7	0.0	47	59	1,049

Personal communication M.Kreuzer (BfS)
Values calculated with the software developed in the Alpha-Risk project (Marsh et al., Radiat. Prot. Dosim. 2008, **130**:101-6)

Dosimetry for uranium miners

Introduction

Methods

The WISMUT cohort

The EU Concerted action CURE

The CURE project: Concerted Uranium Research in Europe

- Task of the **DoReMi** European Network of Excellence
- **9 Participants** (IRSN, BfS, PHE, Nuvia, AWE, SCK•CEN, SURO, CREAL, IC)
- **6 Countries** (France, UK, Germany, Belgium, Czech Republic, Spain)
- **Coordination: IRSN**

- **WP1:** Epidemiology (R.Haylock, PHE, UK)
- **WP2:** Dosimetry (E.Blanchardon, IRSN, France)
- **WP3:** Biology (M.Gomolka, BfS, Germany)
- **WP4:** Coordination (D.Laurier, IRSN, France)
- **UWG:** Uncertainties (A.Giussani, BfS, Germany)

CURE WP2 Dosimetry: Development of the dosimetric protocol

Apply up-to-date ICRP biokinetic and dosimetric models

- Revised Human Respiratory Tract Model (ICRP Publ. 130)
- Human Alimentary Tract Model (ICRP Publication 100)
- NCRP wound model (NCRP Report 156)
- ICRP OIR systemic models for uranium (U), thorium (Th), radium (Ra), actinium (Ac), protactinium (Pa), polonium (Po), lead (Pb), bismuth (Bi) and radon gas (Rn) assuming independent kinetics
- Radionuclides transformation data from ICRP publication 107
- Reference computational phantoms from ICRP Publication 110
- Dose conversion coefficients for external irradiation (ICRP Publication 116)

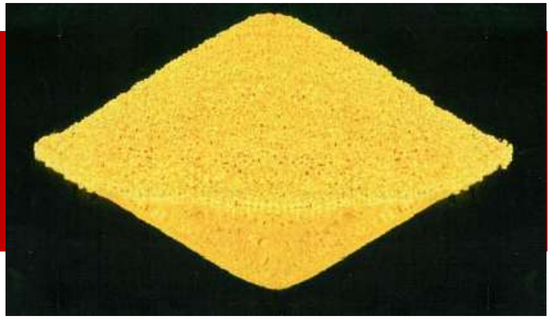
CURE WP2 Dosimetry: Development of the dosimetric protocol

- Evaluate annual absorbed doses (mGy/year):
  - to regions of the lung: alveolar-interstitial region (AI), secretory and basal cells of the bronchi (BB_{sec}, BB_{bas}), sensitive cells of the bronchioles (bb),
  - to systemic tissues: red bone marrow, kidney, liver, brain, heart, endosteum,
  - to other tissues: extra-thoracic airways (mouth/nose), stomach, small intestine, colon, lymph nodes.
- Evaluate separately contributions
  - from high-LET and low-LET radiation
  - from uranium, radon gas, radon progeny, long-lived radionuclides, and from external irradiation.

WP2 Dosimetry: Miners' and millers' exposure assessment

- 0: Hewer + wet drilling + diesel + good ventilation
- 1: Hewer + wet drilling + no diesel + good ventilation
- 2: Hewer + wet drilling + no diesel + medium ventilation
- 3: Hewer + wet drilling+ no diesel + bad ventilation
- 4: Hewer + dry drilling + no diesel + bad ventilation
- 5: Other (underground) + diesel+ good ventilation
- 6: Other (underground) + no diesel + good ventilation
- 7: Other (underground) + no diesel + medium ventilation
- 8: Other (underground) + no diesel + bad ventilation
- 9: Other (surface)
- 10: Miller (ore) + good ventilation
- 11: Miller (ore) + medium ventilation
- 12: Miller (ore) + bad ventilation
- 13: Miller (non-calcined samples) + good ventilation
- 14: Miller (non-calcined samples) + medium ventilation
- 15: Miller (non-calcined samples) + bad ventilation
- 16: Miller (ore and non-calcined samples) + good ventilation
- 17: Miller (ore and non-calcined samples) + medium ventilation
- 18: Miller (ore and non-calcined samples) + bad ventilation
- 19: Miller (calcined samples) + good ventilation
- 20: Miller (calcined samples) + medium ventilation
- 21: Miller (calcined samples) + bad ventilation
- 19: Miller (calcined and non-calcined samples) + good ventilation
- 20: Miller (calcined and non-calcined samples) + medium ventilation
- 21: Miller (calcined and non-calcined samples) + bad ventilation
- 22: Miller (ore and calcined samples) + good ventilation
- 23: Miller (ore and calcined samples) + medium ventilation
- 24: Miller (ore and calcined samples) + bad ventilation
- 25: Miller (ore, calcined and non-calcined samples) + good ventilation
- 26: Miller (ore, calcined and non-calcined samples) + medium ventilation
- 27: Miller (ore, calcined and non-calcined samples) + bad ventilation

WP2 Dosimetry: Parameter definition for millers' exposure assessment



Equilibrium factor, F

The value depends upon the ventilation:

- Poor: *F* = 0.5 - 0.6; basement
- Medium: *F* = 0.3 - 0.4; natural ventilation with windows open
- Good: *F* = 0.2 – 0.3; forced ventilation installed.

Process

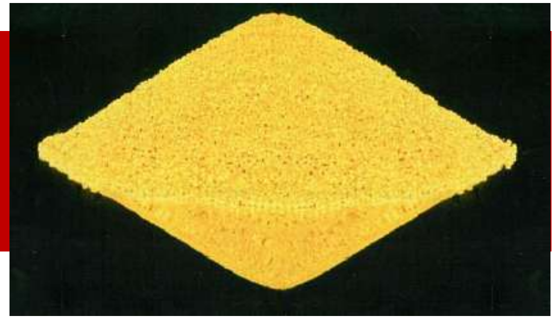
- Grinding — Ore (Moderately soluble; Type M)
- Leaching to dissolve uranium — Relatively Soluble (Type F/M)

Separation of leach solution from waste solids

- Solvent extraction — Relatively Soluble (Type F/M)
  (to remove uranium from leach solution)
- Yellowcake precipitation — Relatively Soluble (Type F/M)
  - ammonium diuranate (ADU) or sodium diuranate
- Drying/calcining — Moderately to insoluble (Type M/S)

Important source of uncertainty for lung doses and systemic doses

WP2 Dosimetry: Parameter definition for millers' exposure assessment



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- Good: $F = 0.2 - 0.3$; forced ventilation installed.

Process

- Grindi
- Leach

Separatio

- Solver

(

- Yellow

➢

- Drying

Table 6: Uranium absorption parameter values for millers.

Processed material	f_r	s_r (d^{-1})	s_s (d^{-1})	f_A
Uranium ore	0.2	0.8	1.4E-3	0.004
Non-calcined samples	0.8	1	5.0E-3	0.016
Calcined samples	0.3	3	5.0E-3	0.006

Important source of uncertainty for lung doses and systemic doses

UWG: Uncertainty Working Group

Main aim

- to identify and investigate all the possible sources of uncertainties which may affect the processes of dose estimation and risk evaluation.

Work performed

- Uncertainty matrix: Identification of uncertainty sources as a prerequisite for their reduction and/or quantification.
- Case studies

  Dose assessment procedure:
  - Choice of pulmonary absorption type
  - Chronic vs acute

  Classical and molecular epidemiology:
  - Availability of information of smoking to be tested
  - Temporal issues not relevant

  Biology:
  - Biomarker(s)?

Concerted Uranium Research

Thanks to the WISMUT people and to the full CURE team:

Sophie ANCELET, Will ATKINSON, Sarah BAATOUT, Christophe BADIE, Gary BETHEL, Jean-Marc BERTHO, Derek BINGHAM, Eric BLANCHARDON, Richard BULL, Elisabeth CARDIS, Cécile CHALLETON-de VATHAIRE, Rupert COCKERILL, Estelle DAVESNE, Damien DRUBAY, Teni EBRAHIMIAN, Hilde ENGELS, Nora FENSKE, Michael GILLIES, Maria GOMOLKA, James GRELLIER, Stephane GRISON, Yann GUEGUEN, Janet HALL, Richard HAYLOCK, Sabine HORNHARDT, Chrystelle IBANEZ, Sylwia KABACIK, Lukas KOTIK, Michaela KREUZER, Olivier LAURENT, Dominique LAURIER, Anne-Laure LE BACQ, James MARSH, Dietmar NOSSKE, Jackie O'HAGAN, Eileen PERNOT, Matthew PUNCHER, Roel QUINTENS, Estelle RAGE, Tony RIDDELL, Laurence ROY, Eric SAMSON, Christina SOBOTZKI, Maamar SOUIDI, Ladislav TOMASEK, Michelle TURNER, Nina WEILAND, Sergey ZHIVIN